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## Global Ecology and Conservation

journal homepage: <http://www.elsevier.com/locate/gecco>

Original Research Article

# An assessment of the representation of ecosystems in global protected areas using new maps of World Climate Regions and World Ecosystems



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## ARTICLE INFO

## Article history:

Received 31 October 2019

Received in revised form 25 November 2019

Accepted 25 November 2019

## ABSTRACT

Representation of ecosystems in protected area networks and conservation strategies is a core principle of global conservation priority setting approaches and a commitment in Aichi Target 11 of the Convention on Biological Diversity. The 2030 Sustainable Development Goals (SDGs) explicitly call for the conservation of terrestrial, freshwater, and marine ecosystems. Accurate ecosystem distribution maps are required to assess representation of ecosystems in protected areas, but standardized, high spatial resolution, and globally comprehensive ecosystem maps have heretofore been lacking. While macroscale global ecoregions maps have been used in global conservation priority setting exercises, they do not identify distinct localized ecosystems at the occurrence (patch) level, and instead describe large ecologically meaningful areas within which additional conservation planning and management are necessary. We describe a new set of maps of globally consistent climate regions and ecosystems at a much finer spatial resolution (250 m) than existing ecological regionalizations. We then describe a global gap analysis of the representation of these ecosystems in protected areas. The new map of terrestrial World Ecosystems was derived from the objective development and integration of 1) global temperature domains, 2) global moisture domains, 3) global landforms, and 4) 2015 global vegetation and land use. These new terrestrial World Ecosystems do not include either freshwater or marine ecosystems, but analog products for the freshwater and marine domains are in development. A total of 431 World Ecosystems were identified, and of these a total of 278 units were natural or semi-natural vegetation/environment combinations, including different kinds of forestlands, shrublands, grasslands, bare areas, and ice/snow regions. The remaining classes were different kinds of croplands and settlements. Of the 278 natural and semi-natural classes, 9 were not represented in global protected areas with a strict biodiversity conservation management objective (IUCN management categories I-IV), and an additional 206 were less

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than 8.5% protected (half way to the 17% Aichi Target 11 goal). Forty four classes were between 8.5% and 17% protected (more than half way towards the Aichi 17% target), and only 19 classes exceeded the 17% Aichi target. However, when all protected areas (IUCN management categories I-VI plus protected areas with no IUCN designation) were included in a separate global gap analysis, representation of ecosystems increases substantially, with a third of the ecosystems exceeding the 17% Aichi target, and another third between 8.5% and 17%. The overall protection (representation) of global ecosystems in protected areas is considerably less when assessed using only strictly conserved protected areas, and more if all protected areas are included in the analysis. Protected area effectiveness should be included in further evaluations of global ecosystem protection. The ecosystems with the highest representation in protected areas were often bare or sparsely vegetated and found in inhospitable environments (e.g. cold mountains, deserts), and the eight most protected ecosystems were all snow and ice ecosystems. In addition to the global gap analysis of World Ecosystems in protected areas, we report on the representation results for the ecosystems in each biogeographic realm (Neotropical, Nearctic, Afrotropical, Palearctic, Indomalayan, Australasian, and Oceania).

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## 1. Introduction

The partitioning of the planet into ecological zones has been implemented in a number of different approaches and scales for a variety of differing applications (e.g. Udvardy, 1975; Takhtajan, 1986; Olson et al., 2001; Longhurst, 2007; Bailey, 2009; Metzger et al., 2013; Sayre et al., 2014; Sayre et al., 2017), and underpins the scientific discipline known as ecosystems geography (Bailey, 2009). Early attempts at ecological regionalization were based on the extensive field-based knowledge of ecosystem geographers who reviewed existing maps and applied scientific principles to develop new characterizations (e.g. White, 1983), usually at generally coarse spatial resolutions. Today, improved computing technologies and a wealth of earth surface data now permit more quantitative and objective global ecosystem mapping approaches at higher spatial resolutions (e.g. 250 m; Sayre et al., 2014).

### 1.1. Ecosystem mapping for conservation priority setting

The global biodiversity conservation community routinely uses ecoregions in conservation planning and priority setting (Groves, 2003; Dinerstein et al., 2017), and global resource assessments like the United Nations Food and Agriculture Organization (FAO) Forest Resources Assessments (FRAs) use ecological zones for analysis and reporting (FAO, 2001a; FAO, 2012). The principle of ecosystems representation in protected areas and other conservation management strategies is a foundational element of conservation priority setting, and systematic conservation planning approaches (Possingham et al., 2006) include rigorous analysis of ecosystem representation, persistence, complementarity and efficiency as reserve selection criteria. The 2015 commitment by nations to the United Nations Sustainable Development Goals (SDGs, <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>) has focused attention on the conservation and sustainable management of terrestrial, freshwater, and marine ecosystems, highlighting the need for maps of their distributions and condition.

Ecoregions are often recognized as large, ecologically meaningful planning areas within which a robust 'portfolio' analysis is needed to identify the biodiversity entities (generally species and ecosystems) which merit conservation attention. These ecoregion portfolios can be used as conservation blueprints for the development of on-the-ground and in-the-water conservation strategies. For global conservation planning purposes ecoregions are considered macroscale ecosystems and can be prioritized, resulting in lists of priority ecosystems. Evaluation of the global conservation importance of the World Wildlife Fund ecoregions (Olson et al., 2001), for example, initially resulted in the list of "Global 200" (Olson and Dinerstein, 2002; UNEP (United Nations Environment Program), 1992; Watson et al., 2016) priority ecoregions. More recently, a priority set of WWF ecoregions has been identified which could be used to conserve 'half of the terrestrial realm' (Dinerstein et al., 2017), in support of E.O. Wilson's aspirational "Half Earth" vision (Wilson, 2016).

However, while ecoregions have often been used to prioritize the conservation importance of large regions, they lack the thematic and spatial resolution necessary for finer scale conservation planning efforts. A transparent, replicable process which resulted in data-derived maps of global ecosystems at a spatial and thematic resolution suitable for local and national conservation planning would represent a considerable advance over current ecoregionalization approaches. A global map of standardized high-resolution ecosystems could enable a more spatially resolved focus on the occurrences of ecologically important areas on the ground, and could facilitate globally consistent fine-scale prioritization of protection actions.

## 1.2. An approach for developing a new set of standardized global climate and ecological settings maps

Given the need for globally consistent and practical climate and ecosystem maps for use in conservation applications, we developed a new set of World Climate Regions and World Ecosystems. To ensure rigor in the consistent representation of lands and the standardized development of the products, and to derive and disseminate them as authoritative data, we adopted the Intergovernmental Panel on Climate Change (IPCC) approach to the definition and development of standardized (default) climate regions and ecological zones. These guidelines, developed in 2006 (IPCC, 2006) and revised in 2019 (IPCC, 2019) define climate and ecological zones as stratification geographies for greenhouse gas inventories. For both the default climate regions and the default ecological zones, formulae and criteria are provided for their development and use in national inventories (IPCC, 2019).

For climate-based stratification units, IPCC recommends 12 classes of climate zones (Table 1). IPCC acknowledges that the development of some of the greenhouse gas assessment parameters was based on the use of this set of climate stratification classes, highlighting the importance of their use by countries for climate change modeling.

For ecological region-based stratification, the IPCC recommends 20 global ecological zones (Table 1), developed by the United Nations Food and Agriculture Organization, and commonly referred to as the FAO Global Ecological Zones (FAO, 2012). For IPCC assessments, these zones are used in biomass calculations, again underscoring their importance for use in national greenhouse gas inventories. The global ecological zones were originally developed (FAO, 2001a) for analysis and reporting of global forest inventories called Forest Resource Assessments (FAO, 2001b; FAO, 2010) and were adopted by the IPCC as standardized stratification geographies for greenhouse gas assessments (IPCC, 2006, 2019). The Global Ecological Zones were developed in a series of regional expert workshops where regional maps were produced, and subsequently compiled and geospatially reconciled at the global level (FAO, 2012). The input regional source maps had scales ranging from 1:4 million to 1:15 million. The Global Ecological Zones map is made available as a GIS resource at <http://www.fao.org/geonetwork/srv/en/main.home?uuiid=2fb209d0-fd34-4e5e-a3d8-a13c241eb61b>.

Building from these *a priori* climate and ecosystem zone typologies, we produced standardized global maps of modified IPCC climate regions and modified FAO ecological zones using best available data at a much higher spatial resolution (250 m). The original classes included in the IPCC default lists of climate regions and ecological zones (Table 1) are not necessarily mutually exclusive, and this inconsistency can be problematic when trying to map the classes. For example, the default list of climate regions includes a class for tropical wet and another class for tropical montane. A particular tropical region, however, may be both mountainous and wet. The IPCC default climate and ecological zone classes recognize the importance of certain biophysical features like environmental moisture, landforms, and vegetation type, but these were not systematically included in the IPCC/FAO conceptual framework. As a result, overlapping classes are possible, complicating their use as stratification and reporting geographies.

An assessment by FAO of their own global ecological zones (FAO, 2012) suggested that future versions could be more objectively and quantitatively developed using increasingly available high-resolution data on climate, terrain, and vegetation. Here, we respond to this suggestion, and produce a more standardized, objective, and higher spatial resolution (250 m) map of global ecosystems, the World Ecosystems. The new World Ecosystems data are intended to be useful for conservation planning, forest resource assessments, IPCC greenhouse gas modeling, ecosystem accounting, and other applications requiring spatially explicit delineation of ecosystem distributions. We make these high resolution globally comprehensive

**Table 1**  
Default set of climate zones and ecological zones recommended for use in national greenhouse gas inventories (IPCC, 2006; FAO 2001a,b).

Climate Zone	Ecological Zone
Tropical moist	Tropical rain forest
Tropical wet	Tropical moist deciduous forest
Tropical dry	Tropical dry forest
Tropical montane	Tropical shrubland
Warm temperate moist	Tropical desert
Warm temperate dry	Tropical mountain systems
Cool temperate wet	Subtropical humid forest
Cool temperate dry	Subtropical dry forest
Boreal moist	Subtropical steppe
Boreal dry	Subtropical desert
Polar moist	Subtropical mountain systems
Polar dry	Temperate oceanic forest
	Temperate continental forest
	Temperate steppe
	Temperate forest
	Temperate mountain systems
	Boreal coniferous forest
	Boreal tundra woodland
	Boreal mountain systems
	Polar

resources available as a standardized complement or alternative to country-specific data development (see Data Availability section below).

Minor modifications were made to the original IPCC typologies to correct for inconsistencies in the original class definitions, and to ensure that the map units produced were spatially mutually exclusive. Our sequential approach to ecosystem mapping was to 1) develop a new set of World Climate Regions, 2) combine these with World Landforms, and 3) combine the climate/landforms product with a World Vegetation/Land Cover product. The resulting World Ecosystems units therefore represent unique combinations of climate region, landform, and vegetation/land cover. We also stratify the World Ecosystems by biogeographic realm, recognizing that the same combinations of climate, landform, and vegetation on different continents may be compositionally different in terms of biodiversity.

## 2. Input data and methods

### 2.1. Climate regions

There are many approaches to mapping climate regions, and the rich tradition of global climate regionalization is acknowledged (see reviews by Essengwanger, 2001; Belda et al., 2014). The criteria set out in the IPCC guidelines follow a modified Köppen approach (Köppen, 1931) emphasizing temperature regimes as the primary determinant. We drew from the IPCC guidance criteria, class names, and class separation thresholds to first develop a World Temperature Domains product. Temperature data from WorldClim version 2 (Fick and Hijmanns, 2017) were used to produce the temperature domains. WorldClim data are interpolated 1 km raster data surfaces derived from temperature and precipitation data collected from 9000 to 60,000 meteorological stations over a 30-year period from 1970 to 2000.

As an important modification to the IPCC guidance, we added a subtropical class to the five IPCC temperature classes, resulting in a total of six temperature domains. The subtropical class was added because the default list of global ecological zones contains subtropical classes, and yet the list of default climate regions (Table 1) does not. To deal with this inconsistency, we divided the original range of mean annual temperatures for the tropical class (18 °C–34 °C) into two classes, subtropical (18 °C–24 °C) and tropical (24 °C–34 °C). The 24 °C threshold was used to separate the tropical and subtropical temperature domains based on the classic life zones characterization of Holdridge (1967). The temperature ranges to delineate the six temperature domains are presented in Table 2.

We then created a simplified World Moisture Domains product based on the value of the aridity index (AI). The AI (mean annual precipitation/potential evapotranspiration) is a very important determinant of the overall moisture regime, especially in temperate, boreal, and polar regions. The AI is a more biologically relevant descriptor of environmental moisture than simply using mean annual precipitation because it also includes a consideration of atmospheric demand for water expressed as potential evapotranspiration (UNEP, 1992). We used the global AI dataset (Trabucco and Zomer, 2009) which was derived from WorldClim version 1 (Hijmans et al., 2005) data and is available at <http://www.cgiar-csi.org/data/global-aridity-and-pet-database#download>.

The World Moisture Domains product uses an aridity index of 0.65 to partition global lands into two classes, arid and humid, which we refer to as the dry and moist domains, respectively. A third class, deserts, is extracted from the dry domain using an AI < 0.05, which is recognized as a hyper-arid class. We created this desert climate class because the list of ecological zones (Table 1) includes desert classes. The World Moisture Domain classes and separation criteria are summarized in Table 3.

The World Temperature Domains layer and the World Moisture Domains layer were then combined to derive a World Climate Regions layer. With six temperature domains and three moisture domains, a total of 18 climate regions is possible.

### 2.2. Ecosystems

To develop the ecosystems, we then added IPCC-recognized biophysical environment attributes to the new climate regions described above. The climate regions data were combined with a four class World Landforms data layer. The World Landforms layer is an aggregation of the global Hammond landforms layer (Karagulle et al., 2017) into four classes representing mountains, hills, plains, and tablelands, extending the 18 climate region classes to 72 possible climate region and landform combinations, called World Climate and Terrain Settings. We then combined the climate and landforms product with an eight class 2015 World Vegetation and Land Cover 2015 data layer. The World Vegetation and Land Cover 2015 layer contains forest,

**Table 2**  
World Temperature Domains and associated ranges of mean annual temperatures (°C).

Temperature Domain	Temperature (°C)
Tropical	24–34
Subtropical	18–24
Warm Temperate	10–18
Cold Temperate	0–10
Boreal	<0
Polar	<0 and all months average < 10

**Table 3**  
World Moisture Domains and associated ranges of mean annual temperatures (°C).

Moisture Domain	Aridity Index
Moist (Humid)	>.65
Dry (Arid)	.05–.65
Desert (Hyperarid)	<.05

shrubland, grassland, cropland, sparsely or non-vegetated (bare) area, settlements, snow and ice, and water classes, and was derived from the 300 m spatial resolution 2015 global land cover data produced by the European Space Agency (ESA, 2017). The 72 climate/terrain settings combined with the eight vegetation classes yields 576 total possible combinations of World Ecosystems, not all of which were realized, and not all of which were vegetated (i.e. settlements, snow and ice, surface water).

### 2.3. Representation analysis

Following the principle of ecosystems representation in conservation planning, many environmental NGOs and governments are now engaged in efforts to conserve a certain percent area of each ecosystem in the planning area. The Aichi Target 11 goal of 17% protection ([www.cbd.int/sp/targets/](http://www.cbd.int/sp/targets/)) of ecosystems is commonly used, but it is also recognized that conservation of as much as 30% or more (e.g. Andren, 1994) of an ecosystem's distribution might be necessary for the ecosystem to provide sufficient habitat for species maintenance. To assess the current status of representation of global ecosystems in global protected areas, we overlaid the World Ecosystems data with the World Database on Protected Areas (WDPA, downloaded July 2019 from: <https://www.protectedplanet.net/>). The WDPA protected area polygons were processed according to the Digital Observatory of Protected Areas (DOPA) methodology (Dubois et al., 2018), which retains protected areas that lack an IUCN management category designation, but which eliminates protected areas lacking legal designations and certain international protected areas.

The global gap analysis was conducted at two levels. For the first assessment, we analyzed ecosystem representation in only those protected areas with an essential conservation management focus (IUCN management categories I, II, III, and IV). The IUCN World Conservation Congress in Amman, Jordan in 2000 produced a member-approved declaration (<https://portals.iucn.org/library/sites/library/files/documents/WCC-2nd-002.pdf>) urging the prohibition of resource extraction from IUCN category I-IV protected areas, while allowing such activity in category V and VI parks. We consider the examples of gap analyses which only incorporate strictly protected areas, and from which resource extraction is generally prohibited (e.g. Rodriguez et al., 2004 for species; Aycrigg et al., 2013 for ecosystems; Van Bruegel et al., 2015 for potential natural vegetation) as more conservative with respect to the focus on conservation-based management.

Other global gap analyses (e.g. Hoekstra et al., 2005 for biomes; Dinerstein et al., 2017 for ecoregions), however, incorporate all protected areas in the gap analysis. The 'all protected areas' approach acknowledges that while resource extraction is generally permitted in category V and VI protected areas, those extractive activities may not necessarily preclude effective biodiversity conservation measures and outcomes. Including all protected areas also allows for the inclusion of protected areas that lack an IUCN management category for some reason (e.g. some countries may not provide that attribute when contributing their data to the WDPA).

Therefore, for a more inclusive assessment, we repeated the global ecosystems representation analysis using all protected areas (IUCN categories I-VI as well as protected areas that lack an IUCN management category designation). In an African multi-country gap analysis of potential natural vegetation, Van Bruegel et al. (2015) reported an effective doubling of percent protection outcomes using all protected areas compared with using IUCN category I-IV parks only, suggesting that using only IUCN category I-IV protected areas may under-report actual ecosystem conservation status. The differences in percent protection outcomes, however, may not reflect differences in management effectiveness.

For both the less inclusive and the more inclusive analyses, the area of the ecosystems included in protected areas was converted to a percentage of the total ecosystem area protected. A level of global protection was assigned to each ecosystem based on the following criteria: unrepresented (0% protection, i.e. the ecosystem does not occur in any protected area), underrepresented (1%–8.5% protection), moderately represented (8.5%–17% protection), and well represented (>17% protection). These categories are based on the Convention of Biological Diversity's Aichi Target 11 protection target goal of 17% (<https://www.cbd.int/sp/targets/>), and are arbitrary, but reflect levels of progress (none, less than half, more than half, and met or exceeded) towards achieving the 17% goal.

### 2.4. Current vs. original ecosystem distributions

The new World Ecosystems map is both globally comprehensive and completely tessellated. As described above, one of the inputs in the ecosystems development process, the World Vegetation and Land Cover layer, characterizes the global distribution of forests, shrublands, grasslands, bare areas, croplands, settlements, snow and ice, and water in 2015. Two of those classes, settlements and croplands, are actually land use categories wherein the natural vegetative cover has been converted into human infrastructure or planted for agricultural production. The settlements and croplands classes were retained and

used to partition the climate/landform units. The retention of the settlements and croplands classes was necessary to produce a fully-tessellated, fully-attributed product. Including settlements and croplands, however, results in a characterization of 'actual' ecosystem distributions, rather than 'potential' ecosystem distributions. Using actual ecosystem distributions has the advantage of characterizing the current distribution of global ecological areas which remain after the conversion to date of natural ecosystems to built-up and planted areas.

For conservation planning, it is also important to understand the magnitude of conversion from natural systems to croplands and settlements because many ecosystems have been greatly reduced from their original distributions prior to significant conversion by humans (Watson et al., 2016). The priority setting process includes setting goals for how much of an ecosystem should be conserved (Tear et al., 2005), and there can be a significant difference between setting a percent protection goal based on the current distribution of an ecosystem versus its pre-disturbance distribution. This is particularly true in the case of ecosystems which have been largely converted and for which only a few remnants of the original distribution remain (e.g. the Atlantic coastal forest of Brazil; Joly et al., 2014). In that case, and assuming a 17% protection goal, two goal setting approaches might be 1) conserve 17% of what exists today (actual), or 2) conserve an area equal to 17% of the original, pre-disturbance distribution (potential). Given that the original distribution of this ecosystem was quite large, the latter approach might result in the need to conserve 100% of what remains today.

We used a global potential natural vegetation (PNV; Hengl et al., 2018) layer to allocate any settlement or cropland pixel in the World ecosystems data layer to its original vegetation type. This allocation was accomplished by a spatial combination of the World Ecosystems and PNV layers, and a replacement of the settlements and croplands attribute with the PNV type at that location. Prior to the spatial union of the two layers, the original classes in the global PNV layer were resampled from 1 km to 250 m to match the spatial resolution of the World Ecosystems data layer, and were reclassified to either forests, shrublands, grasslands, sparsely or non-vegetated, surface water, and snow and ice, consistent with the vegetation and land cover attributes of the World Ecosystems data. The union of the actual ecosystems and the PNV, followed by the replacement of the PNV classes for the settlements and croplands classes, resulted in a map of the original distribution of the ecosystems. This map shows the ecosystem distributions prior to significant human disturbance, and is conceptualized as the sum of current, unconverted ecosystem classes and the corresponding potential vegetation classes for areas that today are converted (croplands and settlements). This global original ecosystems data layer permits the calculation of the extent of conversion of any ecosystem class for any area. The representation analysis for conservation priority setting was conducted using only the actual World Ecosystems data.

## 2.5. Biogeographic stratification

Areas with similar temperature and moisture regimes occur on multiple continents. For example, tropical moist regions are found straddling the equator in the Americas, Africa, Indonesia, etc. (Köppen, 1931). Due to their derivation from climate data, the World Ecosystems are similarly expected to occur on multiple continents. As an example, the ecosystem *Tropical Moist Forest on Plains* is expected to have a widespread global distribution. To accommodate the fact that the species composition in the same ecosystem occurring in different parts of the world would be expected to differ, we incorporated a biogeographic stratification of the World Ecosystems data. Biogeographic variation in species composition of ecosystems is a well-known phenomenon, exemplified by the existence of the Wallace Line (Wallace, 1860) in Indonesia, in which species on either side of the line differ markedly in diversity and evolutionary history. We used a set of seven commonly accepted and geospatially delineated (Olson et al., 2001) global biogeographic realms (Neotropical, Nearctic, Afrotropical, Palearctic, Australasian, Indomalayan, and Oceania) to stratify the World Ecosystems data biogeographically. The representation analyses were then conducted separately for each realm.

## 3. Results

### 3.1. Maps

Maps of World Temperature Domains, World Moisture Domains, and World Climate Regions are presented in Figs. 1–3, respectively. These maps are then followed by the biophysical modifier maps, World Landforms (Fig. 4), and World Climate and Terrain Types (Fig. 5). The World Vegetation and Land Cover 2015 map is presented in Fig. 6, and the new World Ecosystems, as a spatial integration of the climate and terrain units with the vegetation units is presented in Fig. 7. Fig. 8 is a graphic showing the conceptual model and color assignments for the World Ecosystems map.

A total of 431 global ecosystems were mapped (Fig. 7). All classes which represented either settlements or croplands were then removed from the representation analyses, as there was no interest in determining the protection status of these highly converted areas. After removing the two sets of converted classes, 297 natural or semi-natural classes remained. Of these, 19 classes had a total global distribution of less than 10 km<sup>2</sup> each, and so were also removed from the analysis in a 'too small to count' sense. Not including the 19 classes with very small distributions (<10 km<sup>2</sup>), the remaining 278 types ranged in size from 11 km<sup>2</sup> (Polar Desert Snow and Ice on Mountains) to 4,545,432 km<sup>2</sup> (Tropical Moist Forest on Plains). After Tropical Moist Forest on Plains, the next five biggest ecosystem classes are Tropical Desert Sparsely or Non-vegetated on Plains (4,156,205 km<sup>2</sup>), Boreal Moist Forest on Mountains (3,544,054 km<sup>2</sup>), Subtropical Moist Forest on Mountains (3,012,368 km<sup>2</sup>), Boreal Moist Forest on Plains (2,921,729 km<sup>2</sup>), and Cool Temperate Moist Forest on Mountains (2,854,983 km<sup>2</sup>).

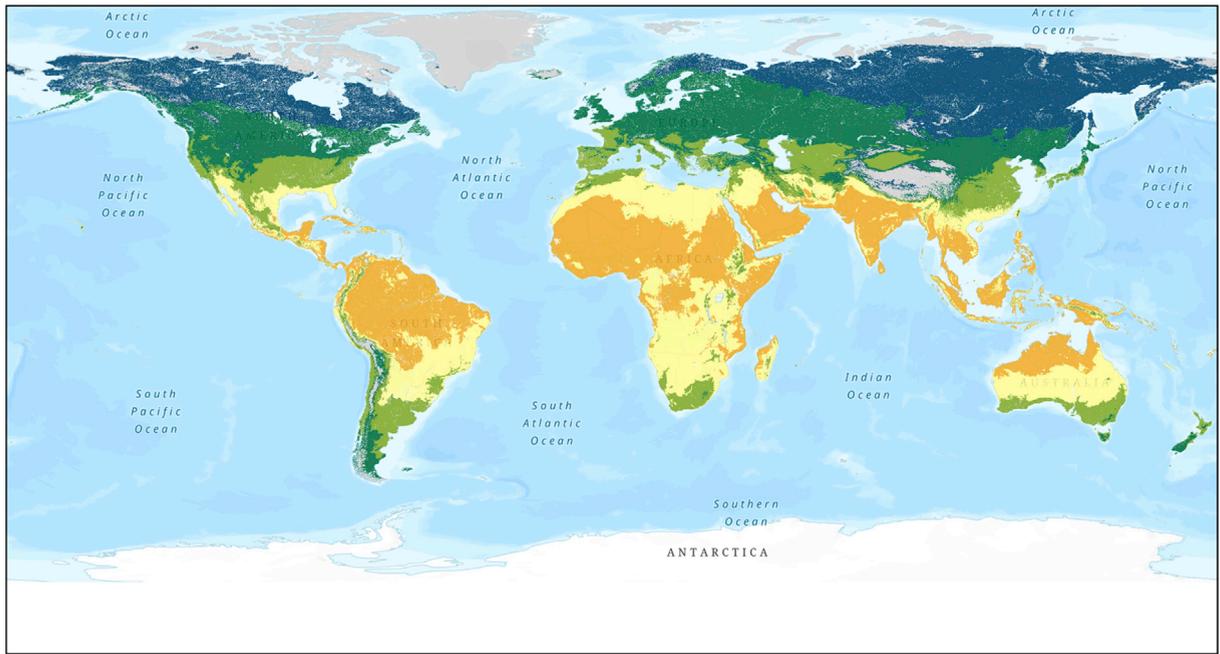


Fig. 1. World Temperature Domains (6 classes).

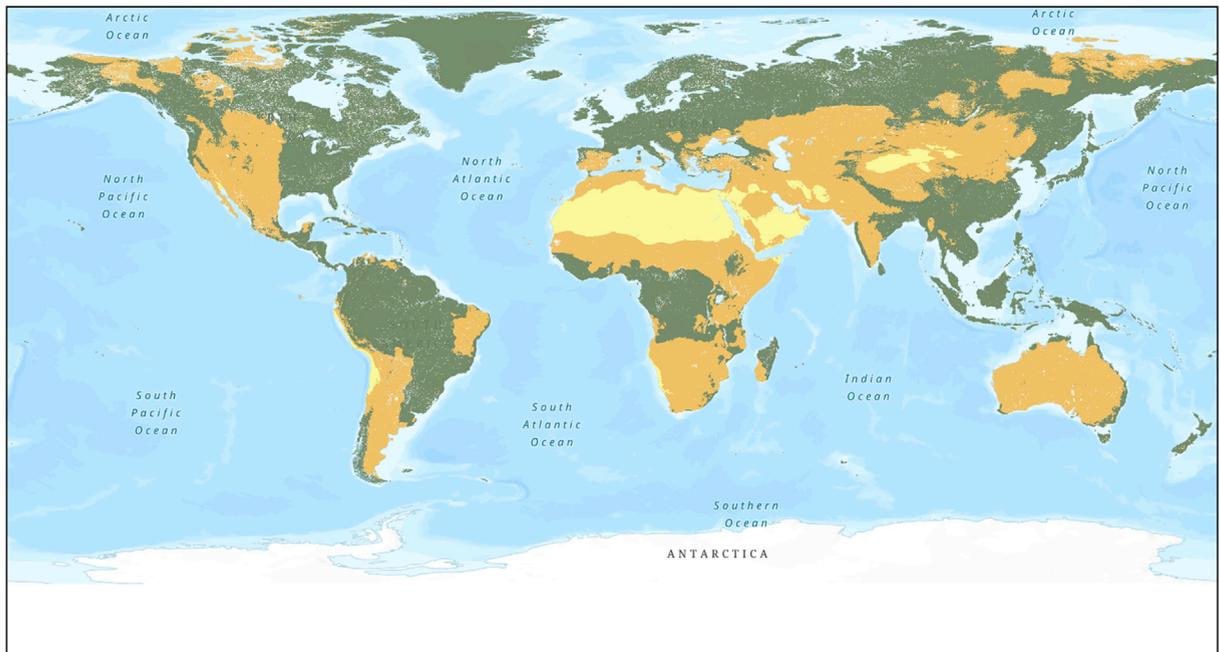
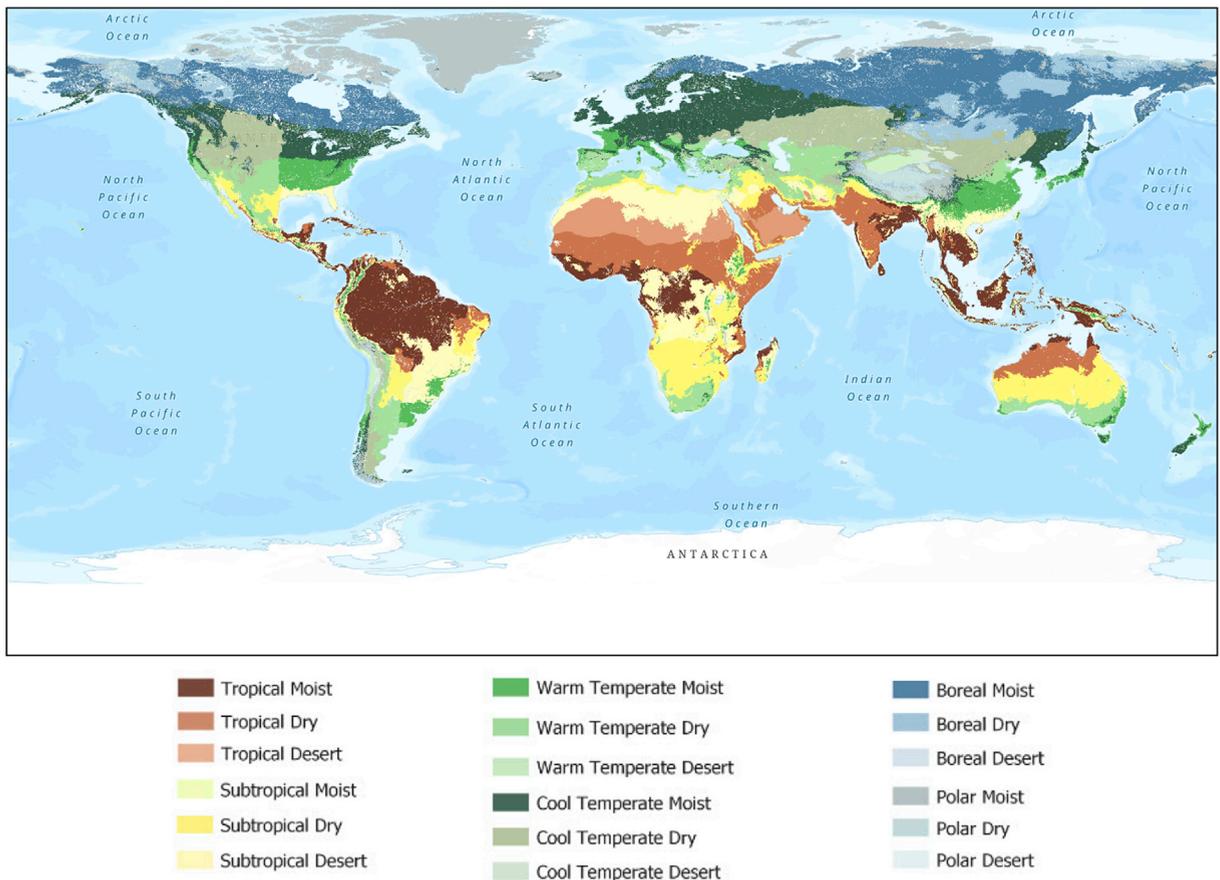


Fig. 2. World Moisture Domains (3 classes).



**Fig. 3.** World Climate Regions (18 classes) produced as a geospatial integration of World Temperature Domains and World Moisture Domains.

Just under half of the 278 classes (138) exceeded a 100,000 km<sup>2</sup> threshold, and the sum of the area of all these classes represents 97% of the total land area on the planet. The other half (140 classes) of the ecosystem types were considerably smaller in size and did not cumulatively account for more than 3% of the total land area.

### 3.2. Ecosystems representation analysis - data and summary

The tabular results from both the less inclusive and more inclusive representation analyses are presented in [Table 4](#), below. [Table 4](#) lists all 278 natural or semi-natural ecosystems and their global areas and percent representation in the global protected area network at both the less inclusive (IUCN I-IV) and more inclusive (all protected areas) levels. The list is presented in order of increasing percent representation in the IUCN I-IV protected areas.

From the IUCN Category I-IV protected areas analysis, only 19 of the 278 ecosystem types (7%) exceeded the current 17% Aichi target (<https://www.cbd.int/sp/targets/>) protection level. A total of 9 ecosystems were not represented whatsoever (0%) in the global protected areas network, and an additional 29 ecosystems were less than 1% represented. An additional 96 types were between 1% and 5% represented for a total of 134 ecosystems that were less than 5% represented. Thus, almost half of the 278 natural and semi-natural ecosystems were less than 5% protected.

From the all protected areas analysis, 91 of the 278 ecosystem types (33%) exceeded the 17% Aichi target, while an additional 105 ecosystems were more than half way towards meeting the target (between 8.5% and 17% represented). The number of ecosystems with less than 5% protection dropped from 134 ecosystems (IUCN Category I-IV protected areas) to 41 ecosystems (all protected areas).

### 3.3. Conversion analysis

In addition to understanding the status of representation of current (actual) ecosystems in the global protected areas network, we also identified the amount of conversion of each ecosystem from its original distribution using the potential

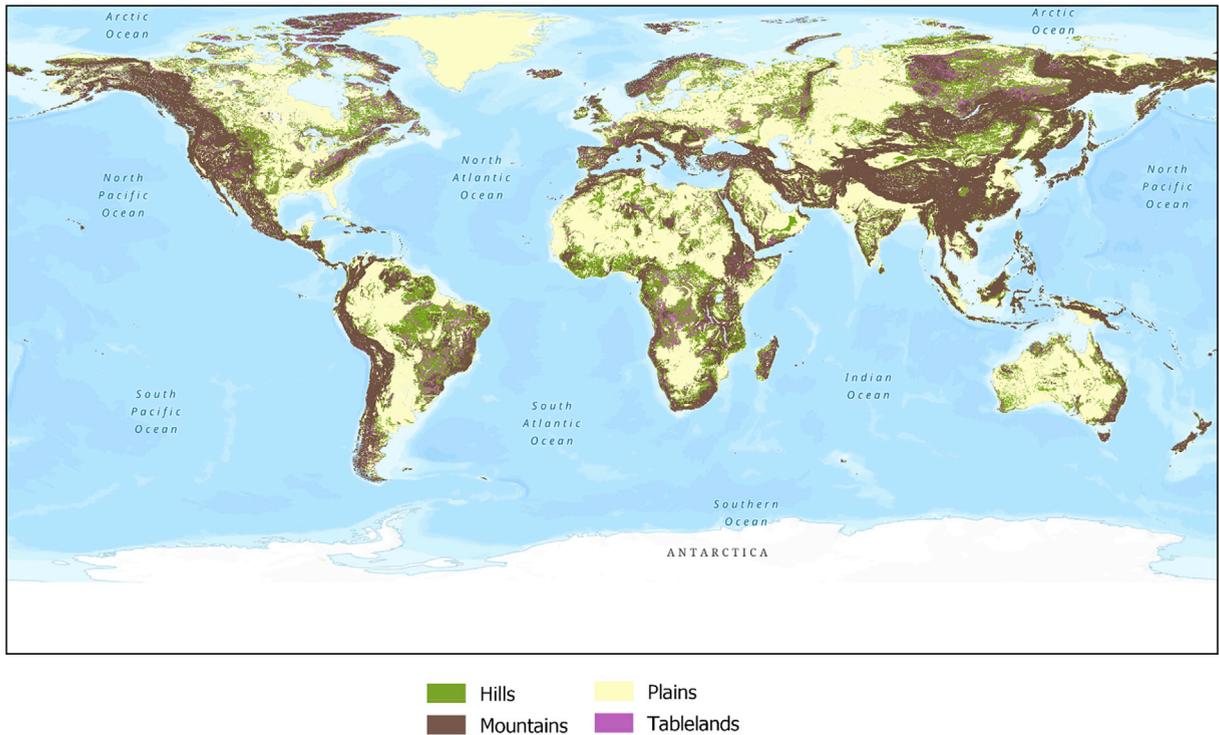


Fig. 4. World Landforms (4 classes) produced as an aggregation of global Hammond landforms.

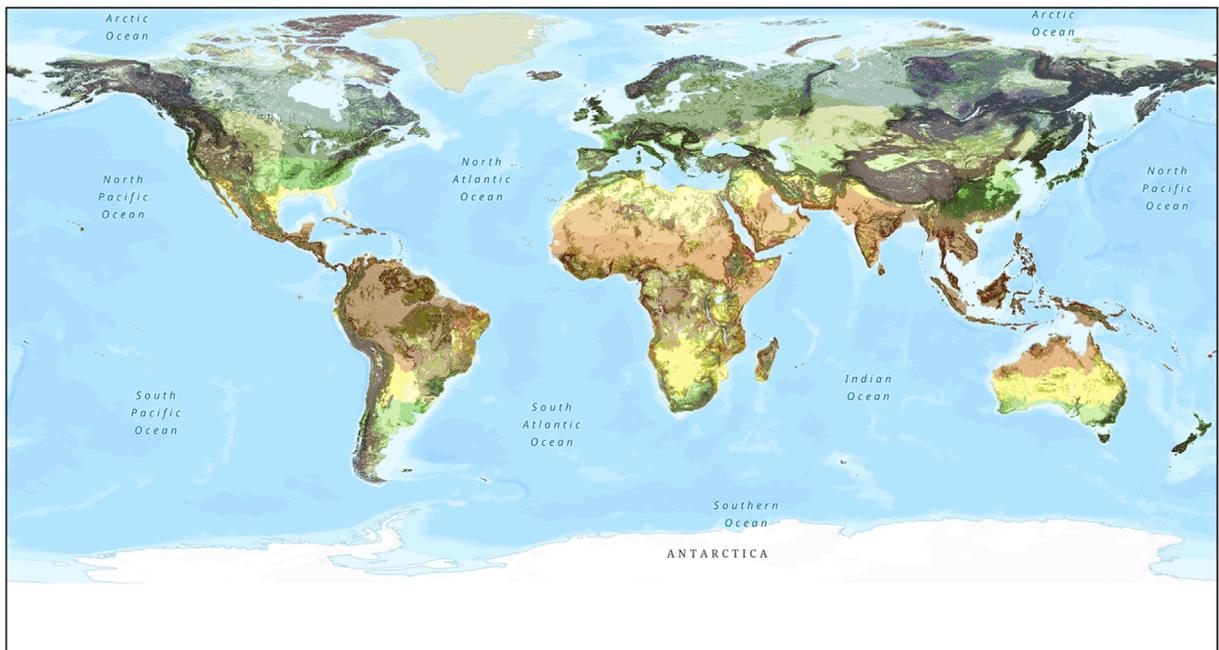
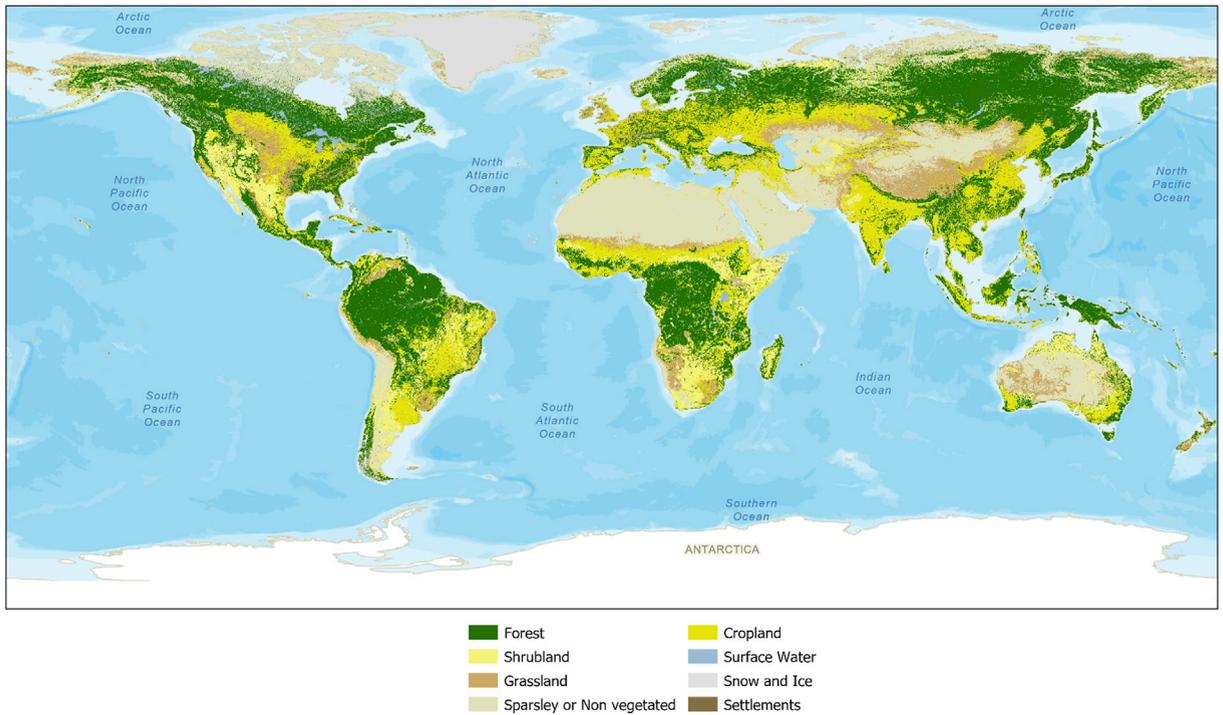
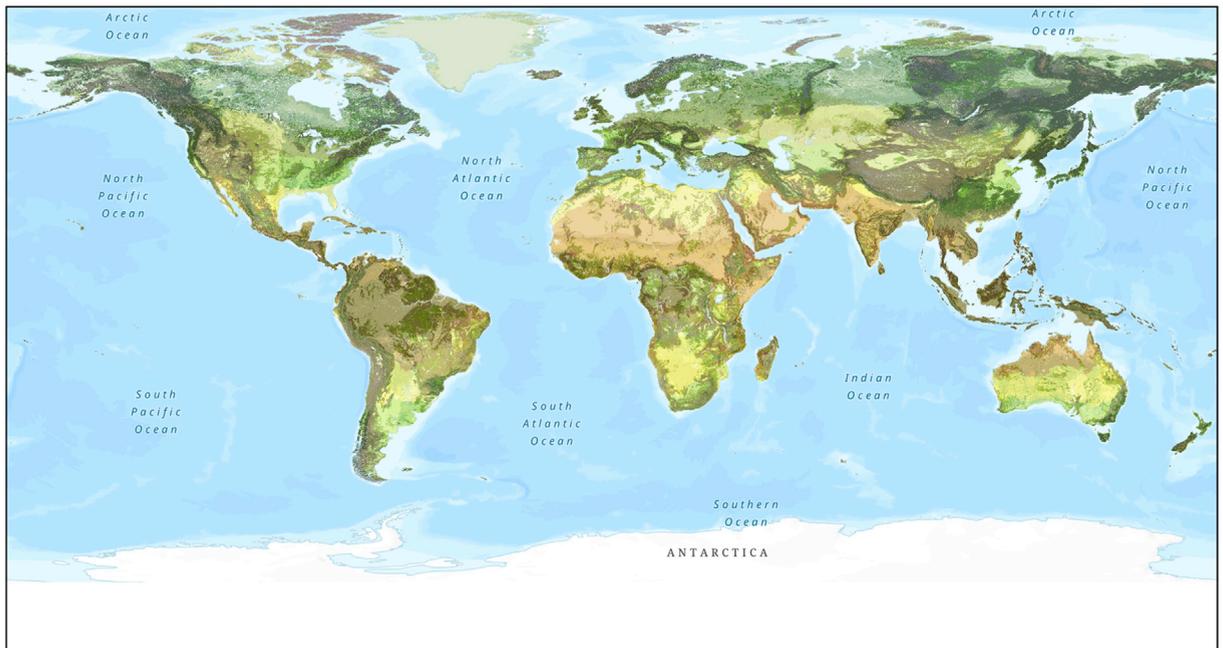


Fig. 5. World Climate and Terrain Settings (72 classes) produced as a geospatial integration of World Climate Regions and World Landforms.

natural vegetation (PNV) approach described above. By allocating each settlement or cropland pixel into its potential vegetation type, we were able to characterize the original distribution of each ecosystem as the sum of the actual ecosystem area and the potential ecosystem area. The global percent conversion of the World Ecosystem types grouped by their vegetation/land cover attributes is presented in [Table 5](#).



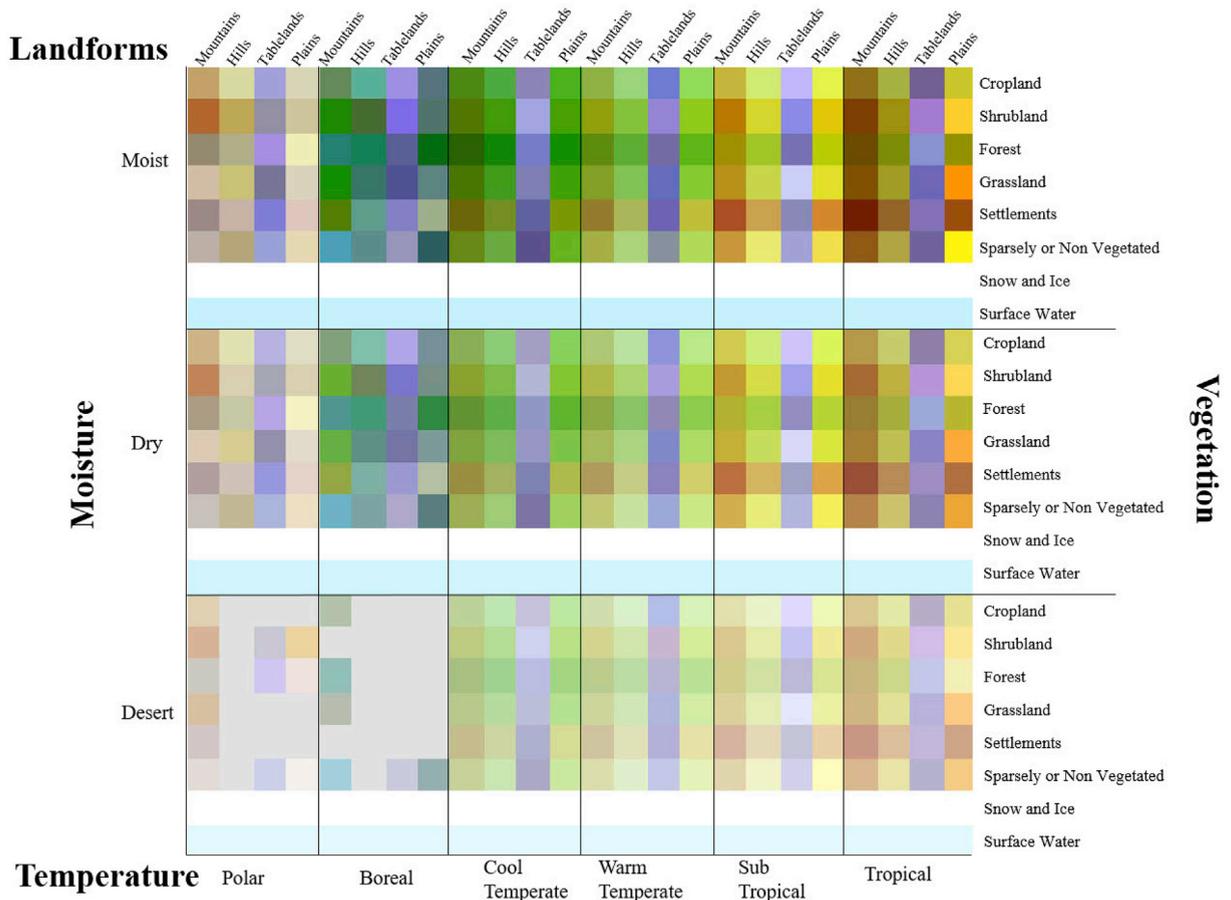
**Fig. 6.** World Vegetation and Land Cover 2015 (8 classes), produced as an aggregation of the 2015 European Space Agency's Climate Change Initiative (CCI) Land Cover data.



**Fig. 7.** World Ecosystems (431) produced as a geospatial integration of World Climate and Terrain Settings and World Vegetation and Land Cover 2015.

### 3.4. Representation analysis by realms

In order to introduce a biogeographic dimension into the analysis of the representation of ecosystems in global protected areas, the ecosystems were subset by biogeographic realms, as described above. [Table 6](#) shows the number of ecosystems in



**Fig. 8.** Legend block showing World Ecosystems as an integration of climate (temperature regime, moisture regime), landform, and vegetation. Each individual cell in the matrix represents an individual ecosystem and displays its color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

each level of representation, by realm. When the 431 globally aggregated World Ecosystems are disaggregated by realm (i.e. realm is used as a classifier along with climate, landform and vegetation/land cover), a total of 1778 ecosystems are identified globally, of which 1225 are natural or semi-natural ecosystems. Table 6 characterizes the representation of these 1225 realm-segregated ecosystems in protected areas.

#### 4. Discussion

##### 4.1. A new map of World Ecosystems

We developed a new World Ecosystems map and associated global data layers on climate, landforms, and vegetation/land cover. These high-resolution (250 m), open-data products are globally consistent and replicable. They are consistent with IPCC and FAO development logic and class separation criteria but have a higher thematic resolution (greater number of class types) to correct for inconsistencies which arise when attempting to objectively derive the FAO ecological zones from the IPCC climate regions using additional biophysical attributes. The new ecosystems were developed in a spatially mutually exclusive fashion by assuming a hierarchy of importance from highest to lowest as Climate Region, Landform, and Vegetation/Land Cover. This allowed the subdivision of every climate region into its constituent landforms (mountains, tablelands, hills, and plains) and a subsequent subdivision of these climate/landform combined units by vegetation type. This allows for the ability to separate, for example, tropical moist montane forests and tropical moist forests in non-mountainous regions, eliminating an inconsistency in the IPCC/FAO definitions.

From the first appearance of the word ecosystems in the scientific literature, often attributed to Tansley (1935), to their definition in Odum's (1953) seminal textbook on ecology, and subsequently, ecosystems have been understood as systems of biotic communities interacting with their physical environment. Implicit in this definition is that ecosystems are comprised of a biotic complex and an abiotic complex. Adhering to this fundamental definition of ecosystems, the World Ecosystems are

**Table 4**

The total area and percent representation of the 278 natural and semi-natural World Ecosystems in IUCN I-IV protected areas only (column 3) and all protected areas (column 4). The list of ecosystems is presented in increasing order of percent representation of the ecosystems in the more strictly conserved (IUCN I-IV, column 3) protected areas.

World Ecosystem name	Area (km <sup>2</sup> )	Representation in IUCN category I-IV protected areas (%)	Representation in IUCN category I-VI protected areas (%)
Boreal Desert Grassland on Mountains	1803	0	0.00
Boreal Desert Sparsely or Non-vegetated on Mountains	1530	0	0.00
Cool Temperate Desert Shrubland on Hills	38	0	0.00
Polar Desert Shrubland on Tablelands	48	0	0.00
Tropical Desert Forest on Tablelands	273	0	0.00
Cool Temperate Desert Shrubland on Plains	481	0	1.40
Tropical Desert Forest on Mountains	581	0	3.34
Polar Desert Snow and Ice on Mountains	11	0	3.92
Polar Desert Sparsely or Non-vegetated on Plains	163	0	55.79
Cool Temperate Desert Grassland on Plains	18,883	0.001	0.001
Cool Temperate Desert Grassland on Mountains	33,683	0.006	0.006
Cool Temperate Desert Grassland on Hills	1500	0.03	0.04
Polar Desert Grassland on Mountains	951	0.03	0.09
Warm Temperate Desert Forest on Mountains	108	0.05	0.66
Tropical Desert Forest on Plains	978	0.07	11.17
Tropical Desert Grassland on Tablelands	804	0.08	1.48
Cool Temperate Desert Grassland on Tablelands	951	0.09	0.09
Tropical Desert Forest on Hills	453	0.12	0.28
Tropical Desert Shrubland on Tablelands	2436	0.12	0.86
Polar Moist Snow and Ice on Plains	15,85,468	0.14	38.60
Polar Dry Snow and Ice on Hills	178	0.15	1.07
Warm Temperate Moist Grassland on Plains	2,96,173	0.16	2.35
Tropical Desert Grassland on Hills	1870	0.2	1.45
Tropical Desert Shrubland on Hills	4168	0.23	2.20
Warm Temperate Moist Grassland on Hills	2,22,905	0.25	2.35
Warm Temperate Dry Grassland on Hills	2,64,787	0.27	3.39
Warm Temperate Desert Grassland on Plains	22,677	0.32	0.39
Polar Desert Sparsely or Non-vegetated on Tablelands	321	0.4	0.40
Warm Temperate Desert Shrubland on Plains	2926	0.41	5.05
Warm Temperate Desert Sparsely or Non-vegetated on Plains	3,23,191	0.5	0.89
Tropical Desert Shrubland on Mountains	10,054	0.6	3.34
Warm Temperate Dry Grassland on Tablelands	75,227	0.61	4.10
Polar Dry Grassland on Hills	51,215	0.64	12.26
Subtropical Desert Sparsely or Non-vegetated on Plains	26,85,510	0.69	3.49
Cool Temperate Dry Grassland on Hills	7,24,564	0.78	2.05
Polar Dry Grassland on Tablelands	16,632	0.82	8.71
Polar Moist Grassland on Plains	50,987	0.84	20.59
Cool Temperate Dry Grassland on Tablelands	1,63,488	0.99	2.71
Tropical Desert Grassland on Plains	7551	1.18	7.30
Warm Temperate Moist Grassland on Tablelands	70,487	1.22	4.09
Warm Temperate Desert Grassland on Tablelands	143	1.26	10.13
Tropical Desert Grassland on Mountains	2557	1.31	13.13
Warm Temperate Desert Grassland on Hills	1655	1.33	1.90
Cool Temperate Dry Grassland on Mountains	8,26,432	1.4	3.31
Polar Dry Snow and Ice on Plains	220	1.42	4.96
Warm Temperate Dry Shrubland on Hills	4,75,972	1.48	4.41
Tropical Moist Grassland on Tablelands	16,814	1.48	8.32
Polar Moist Grassland on Hills	29,729	1.53	14.60
Warm Temperate Dry Sparsely or Non-vegetated on Hills	3,23,419	1.54	8.80
Warm Temperate Dry Grassland on Mountains	4,80,653	1.63	5.79
Warm Temperate Moist Shrubland on Plains	53,194	1.68	23.02
Subtropical Desert Grassland on Hills	4398	1.74	2.90
Warm Temperate Desert Shrubland on Hills	219	1.79	21.34
Warm Temperate Moist Sparsely or Non-vegetated on Plains	3082	1.87	13.03
Cool Temperate Moist Grassland on Hills	1,34,025	1.89	13.59
Warm Temperate Dry Shrubland on Tablelands	1,56,773	1.95	5.62
Tropical Moist Sparsely or Non-vegetated on Tablelands	1280	1.96	13.96
Cool Temperate Dry Sparsely or Non-vegetated on Plains	12,20,133	1.97	4.14
Subtropical Moist Grassland on Mountains	1,29,111	1.97	7.93

Table 4 (continued)

World Ecosystem name	Area (km <sup>2</sup> )	Representation in IUCN category I-IV protected areas (%)	Representation in IUCN category I-VI protected areas (%)
Warm Temperate Moist Forest on Plains	3,86,214	1.97	9.89
Warm Temperate Dry Sparsely or Non-vegetated on Plains	9,92,020	1.98	6.95
Tropical Moist Grassland on Hills	89,830	1.99	6.28
Warm Temperate Moist Shrubland on Hills	19,524	1.99	7.05
Subtropical Desert Grassland on Plains	3374	2.04	8.33
Polar Dry Sparsely or Non-vegetated on Hills	84,835	2.06	8.24
Cool Temperate Desert Shrubland on Mountains	11,810	2.06	10.83
Warm Temperate Desert Shrubland on Mountains	23,376	2.15	2.68
Warm Temperate Moist Grassland on Mountains	1,76,172	2.2	9.35
Cool Temperate Dry Grassland on Plains	10,17,480	2.26	4.50
Tropical Desert Sparsely or Non-vegetated on Hills	9,54,203	2.36	6.71
Polar Dry Shrubland on Hills	2849	2.42	79.82
Cool Temperate Moist Grassland on Tablelands	49,930	2.56	18.92
Polar Moist Shrubland on Plains	37,624	2.58	32.43
Polar Moist Sparsely or Non-vegetated on Plains	7,27,282	2.59	27.21
Subtropical Moist Shrubland on Hills	2,62,590	2.67	11.02
Warm Temperate Moist Forest on Hills	3,55,814	2.72	7.72
Warm Temperate Dry Sparsely or Non-vegetated on Mountains	8,34,991	2.74	9.17
Tropical Dry Sparsely or Non-vegetated on Hills	3,99,939	2.76	6.77
Warm Temperate Moist Shrubland on Tablelands	19,807	2.81	8.35
Tropical Dry Sparsely or Non-vegetated on Mountains	4,01,978	2.87	6.17
Polar Desert Shrubland on Mountains	7645	2.96	15.81
Polar Dry Sparsely or Non-vegetated on Tablelands	28,174	2.98	8.28
Cool Temperate Desert Sparsely or Non-vegetated on Plains	1,09,744	3.03	4.20
Polar Dry Sparsely or Non-vegetated on Plains	2,14,634	3.08	13.41
Cool Temperate Dry Shrubland on Hills	1,42,261	3.12	4.42
Subtropical Moist Shrubland on Plains	2,27,461	3.12	19.09
Tropical Desert Sparsely or Non-vegetated on Tablelands	1,34,738	3.14	11.80
Warm Temperate Dry Grassland on Plains	2,93,060	3.19	9.25
Warm Temperate Dry Sparsely or Non-vegetated on Tablelands	1,12,210	3.22	12.56
Polar Dry Grassland on Mountains	9,40,507	3.26	6.66
Tropical Moist Grassland on Mountains	43,999	3.27	10.35
Warm Temperate Moist Forest on Tablelands	2,02,633	3.28	10.79
Tropical Dry Sparsely or Non-vegetated on Tablelands	90,194	3.3	7.32
Subtropical Dry Sparsely or Non-vegetated on Mountains	5,47,647	3.33	11.55
Polar Moist Forest on Hills	3933	3.41	12.37
Subtropical Moist Grassland on Hills	85,505	3.47	6.48
Subtropical Dry Grassland on Mountains	2,54,297	3.5	15.10
Boreal Dry Grassland on Hills	1,37,929	3.59	7.31
Warm Temperate Desert Sparsely or Non-vegetated on Mountains	2,01,681	3.64	8.88
Boreal Moist Grassland on Hills	1,30,772	3.68	12.05
Warm Temperate Moist Sparsely or Non-vegetated on Hills	1818	3.7	14.63
Polar Dry Forest on Tablelands	187	3.71	4.16
Cool Temperate Moist Sparsely or Non-vegetated on Hills	9607	3.71	7.04
Subtropical Desert Shrubland on Plains	16,486	3.75	14.01
Subtropical Moist Forest on Plains	6,80,607	3.78	12.66
Cool Temperate Dry Shrubland on Plains	2,14,657	3.82	9.06
Subtropical Dry Sparsely or Non-vegetated on Tablelands	1,26,590	3.89	10.48
Cool Temperate Dry Forest on Tablelands	56,613	3.94	7.91
Subtropical Moist Shrubland on Tablelands	1,44,053	3.98	11.94
Boreal Dry Sparsely or Non-vegetated on Hills	1,49,491	4.03	9.79
Cool Temperate Moist Grassland on Plains	2,26,358	4.07	12.55
Subtropical Desert Forest on Mountains	602	4.09	7.15
Boreal Dry Grassland on Tablelands	29,821	4.09	7.65
Subtropical Desert Sparsely or Non-vegetated on Hills	10,25,414	4.22	11.82
	1,17,911	4.24	10.78

(continued on next page)

Table 4 (continued)

World Ecosystem name	Area (km <sup>2</sup> )	Representation in IUCN category I-IV protected areas (%)	Representation in IUCN category I-VI protected areas (%)
Warm Temperate Desert Sparsely or Non-vegetated on Hills			
Subtropical Desert Grassland on Tablelands	934	4.25	9.68
Tropical Moist Sparsely or Non-vegetated on Mountains	6893	4.27	10.09
Warm Temperate Dry Shrubland on Plains	7,63,051	4.32	7.93
Boreal Moist Forest on Tablelands	9,37,932	4.36	8.90
Tropical Moist Grassland on Plains	2,66,253	4.37	16.56
Tropical Desert Sparsely or Non-vegetated on Plains	41,56,205	4.42	5.52
Subtropical Moist Shrubland on Mountains	5,25,318	4.43	10.53
Cool Temperate Desert Shrubland on Tablelands	371	4.46	4.57
Boreal Moist Grassland on Tablelands	35,848	4.46	8.34
Warm Temperate Desert Forest on Plains	13	4.5	72.79
Boreal Dry Sparsely or Non-vegetated on Tablelands	46,698	4.53	7.99
Subtropical Moist Grassland on Tablelands	35,858	4.58	7.29
Tropical Dry Grassland on Hills	2,11,744	4.58	11.43
Cool Temperate Moist Forest on Hills	11,99,477	4.65	9.26
Tropical Dry Sparsely or Non-vegetated on Plains	23,50,628	4.76	15.03
Cool Temperate Dry Shrubland on Tablelands	91,810	4.86	7.73
Warm Temperate Moist Shrubland on Mountains	1,58,965	4.93	16.06
Subtropical Dry Shrubland on Hills	6,53,127	4.95	18.27
Cool Temperate Dry Sparsely or Non-vegetated on Mountains	7,49,317	4.97	8.64
Tropical Dry Grassland on Mountains	1,11,453	5.01	13.15
Cool Temperate Dry Sparsely or Non-vegetated on Hills	7,15,995	5.08	6.65
Polar Moist Shrubland on Hills	5393	5.09	15.94
Warm Temperate Dry Shrubland on Mountains	10,45,259	5.12	12.46
Subtropical Dry Sparsely or Non-vegetated on Plains	24,94,418	5.16	14.05
Boreal Dry Grassland on Plains	95,093	5.19	10.91
Cool Temperate Moist Forest on Tablelands	5,22,444	5.2	11.70
Cool Temperate Desert Sparsely or Non-vegetated on Mountains	98,924	5.24	7.36
Boreal Dry Forest on Tablelands	2,31,311	5.27	10.83
Subtropical Dry Grassland on Tablelands	47,176	5.27	18.09
Polar Dry Grassland on Plains	41,546	5.29	22.45
Subtropical Dry Sparsely or Non-vegetated on Hills	5,28,475	5.42	12.81
Subtropical Moist Forest on Hills	13,98,493	5.43	15.22
Boreal Moist Forest on Hills	20,84,633	5.45	8.92
Tropical Dry Shrubland on Hills	7,11,721	5.48	15.91
Warm Temperate Desert Grassland on Mountains	2500	5.53	7.62
Cool Temperate Dry Sparsely or Non-vegetated on Tablelands	1,58,268	5.53	7.89
Tropical Moist Shrubland on Hills	3,77,017	5.6	19.36
Warm Temperate Dry Forest on Mountains	5,61,636	5.6	21.84
Subtropical Dry Forest on Mountains	7,53,774	5.61	19.68
Boreal Moist Grassland on Plains	1,50,556	5.65	19.85
Tropical Desert Sparsely or Non-vegetated on Mountains	3,64,302	5.66	15.61
Subtropical Desert Shrubland on Hills	4279	5.66	33.02
Boreal Dry Snow and Ice on Mountains	1201	5.75	12.22
Warm Temperate Desert Shrubland on Tablelands	490	6.09	6.12
Cool Temperate Desert Forest on Mountains	19	6.09	11.73
Tropical Moist Sparsely or Non-vegetated on Hills	3180	6.14	18.06
Subtropical Dry Shrubland on Mountains	9,99,352	6.14	21.03
Cool Temperate Moist Forest on Plains	19,69,664	6.17	12.24
Subtropical Dry Grassland on Hills	2,50,088	6.17	12.65
Cool Temperate Dry Shrubland on Mountains	5,91,941	6.19	9.02
Subtropical Moist Forest on Tablelands	7,74,094	6.19	14.41
Polar Moist Forest on Plains	11,042	6.3	39.00
Subtropical Dry Forest on Tablelands	2,14,431	6.31	18.73
Subtropical Dry Shrubland on Tablelands	2,03,580	6.37	20.93
Tropical Dry Shrubland on Tablelands	1,66,083	6.39	23.22
Boreal Dry Grassland on Mountains	4,76,082	6.42	8.08
Boreal Moist Sparsely or Non-vegetated on Tablelands	1,89,187	6.42	11.53
Polar Moist Sparsely or Non-vegetated on Hills	4,72,055	6.45	11.34

Table 4 (continued)

World Ecosystem name	Area (km <sup>2</sup> )	Representation in IUCN category I-IV protected areas (%)	Representation in IUCN category I-VI protected areas (%)
Boreal Dry Forest on Hills	6,46,088	6.52	12.54
Cool Temperate Desert Sparsely or Non-vegetated on Tablelands	21,297	6.66	6.66
Tropical Dry Grassland on Plains	9,64,176	6.66	12.13
Polar Desert Forest on Mountains	30	6.66	24.29
Cool Temperate Dry Forest on Hills	50,191	6.7	12.25
Boreal Moist Forest on Plains	29,21,729	6.73	9.02
Tropical Moist Shrubland on Tablelands	78,759	6.8	27.96
Boreal Dry Forest on Mountains	8,94,446	6.88	11.82
Polar Dry Snow and Ice on Mountains	60,407	6.88	12.61
Tropical Moist Shrubland on Plains	6,13,966	6.91	28.93
Tropical Dry Forest on Mountains	3,06,806	7.01	16.60
Warm Temperate Moist Forest on Mountains	22,65,851	7.06	15.43
Tropical Moist Forest on Plains	45,45,432	7.08	36.24
Cool Temperate Dry Forest on Mountains	6,30,661	7.11	10.46
Tropical Moist Shrubland on Mountains	2,01,410	7.16	18.63
Boreal Moist Shrubland on Hills	2,74,736	7.21	11.05
Subtropical Dry Forest on Hills	5,22,044	7.27	23.13
Boreal Moist Shrubland on Plains	10,50,529	7.32	11.44
Boreal Moist Shrubland on Tablelands	99,556	7.33	10.73
Tropical Dry Shrubland on Mountains	3,11,581	7.35	19.15
Polar Moist Grassland on Tablelands	11,345	7.4	12.28
Warm Temperate Dry Forest on Tablelands	59,840	7.46	17.69
Boreal Moist Forest on Mountains	35,44,054	7.5	10.74
Subtropical Moist Sparsely or Non-vegetated on Plains	2596	7.52	14.59
Subtropical Moist Sparsely or Non-vegetated on Tablelands	504	7.63	14.74
Boreal Dry Shrubland on Hills	25,602	7.68	11.64
Polar Dry Sparsely or Non-vegetated on Mountains	4,64,152	7.69	16.13
Polar Dry Shrubland on Tablelands	620	7.74	29.16
Boreal Dry Shrubland on Tablelands	8102	7.76	14.92
Polar Desert Sparsely or Non-vegetated on Mountains	10,977	7.79	21.79
Cool Temperate Moist Sparsely or Non-vegetated on Tablelands	6074	7.82	11.24
Boreal Dry Sparsely or Non-vegetated on Mountains	3,23,358	7.86	12.04
Subtropical Moist Grassland on Plains	1,44,448	7.9	9.59
Tropical Dry Shrubland on Plains	19,35,561	7.93	19.94
Polar Moist Forest on Tablelands	2348	8.09	12.26
Cool Temperate Moist Sparsely or Non-vegetated on Plains	15,620	8.17	13.49
Cool Temperate Moist Shrubland on Hills	57,815	8.21	14.97
Tropical Moist Sparsely or Non-vegetated on Plains	17,111	8.24	25.27
Subtropical Dry Forest on Plains	8,01,124	8.29	23.10
Polar Moist Sparsely or Non-vegetated on Tablelands	2,88,866	8.3	11.35
Boreal Dry Shrubland on Mountains	95,461	8.34	18.87
Cool Temperate Moist Grassland on Mountains	4,39,006	8.43	21.44
Polar Moist Snow and Ice on Hills	30,238	8.52	33.63
Boreal Moist Grassland on Mountains	3,56,929	8.56	13.99
Polar Moist Grassland on Mountains	7,22,899	8.59	12.95
Boreal Moist Sparsely or Non-vegetated on Plains	8,62,374	8.66	14.15
Boreal Moist Sparsely or Non-vegetated on Hills	3,84,180	8.85	12.49
Subtropical Moist Sparsely or Non-vegetated on Mountains	7962	8.93	26.05
Warm Temperate Moist Sparsely or Non-vegetated on Tablelands	695	8.96	15.88
Cool Temperate Desert Sparsely or Non-vegetated on Hills	1,30,257	9.19	9.28
Cool Temperate Dry Snow and Ice on Mountains	549	9.2	13.25
Subtropical Dry Shrubland on Plains	17,43,257	9.27	19.54
Tropical Dry Grassland on Tablelands	39,739	9.3	18.35
Cool Temperate Dry Forest on Plains	1,07,625	9.38	17.86
Tropical Dry Forest on Hills	5,39,059	9.41	22.37
Warm Temperate Desert Sparsely or Non-vegetated on Tablelands	42,458	9.6	18.23
Warm Temperate Dry Forest on Hills	97,624	9.68	18.03

(continued on next page)

Table 4 (continued)

World Ecosystem name	Area (km <sup>2</sup> )	Representation in IUCN category I-IV protected areas (%)	Representation in IUCN category I-VI protected areas (%)
Subtropical Dry Grassland on Plains	10,91,866	9.84	20.84
Boreal Moist Shrubland on Mountains	6,99,650	9.9	16.17
Polar Dry Shrubland on Mountains	81,709	9.9	17.33
Polar Moist Shrubland on Tablelands	4323	9.93	16.43
Tropical Moist Forest on Tablelands	4,58,311	10.26	29.67
Boreal Dry Forest on Plains	7,62,522	10.34	14.72
Warm Temperate Moist Sparsely or Non-vegetated on Mountains	11,611	10.4	24.21
Subtropical Moist Forest on Mountains	30,12,368	10.6	21.35
Tropical Dry Forest on Plains	7,26,656	10.62	28.99
Boreal Dry Shrubland on Plains	89,793	10.65	15.85
Subtropical Desert Forest on Plains	372	10.87	26.93
Tropical Dry Forest on Tablelands	81,053	11.18	23.14
Tropical Desert Shrubland on Plains	8367	11.35	22.09
Tropical Moist Forest on Hills	28,47,943	11.42	39.27
Polar Moist Shrubland on Mountains	1,68,806	12.09	22.24
Tropical Moist Forest on Mountains	20,76,010	12.1	30.11
Cool Temperate Moist Forest on Mountains	28,54,983	12.24	22.52
Cool Temperate Moist Shrubland on Plains	1,58,869	12.39	20.80
Subtropical Desert Sparsely or Non-vegetated on Tablelands	2,74,816	12.54	22.25
Boreal Moist Sparsely or Non-vegetated on Mountains	5,84,985	12.59	18.57
Boreal Moist Snow and Ice on Tablelands	759	12.92	13.02
Cool Temperate Moist Shrubland on Tablelands	31,191	12.92	17.66
Subtropical Desert Sparsely or Non-vegetated on Mountains	5,05,825	13.3	23.74
Polar Dry Shrubland on Plains	46,505	14.52	53.52
Polar Dry Forest on Hills	386	15.16	17.92
Subtropical Desert Grassland on Mountains	8759	15.21	29.25
Polar Dry Forest on Mountains	34,626	15.78	18.91
Polar Moist Snow and Ice on Tablelands	55,528	15.82	31.14
Warm Temperate Dry Forest on Plains	1,41,625	16.54	26.12
Boreal Dry Sparsely or Non-vegetated on Plains	2,13,706	17.8	21.46
Subtropical Moist Sparsely or Non-vegetated on Hills	699	18.59	36.77
Polar Moist Sparsely or Non-vegetated on Mountains	9,50,754	18.97	25.81
Polar Moist Forest on Mountains	1,79,170	19.81	30.56
Polar Dry Snow and Ice on Tablelands	77	20.58	24.70
Subtropical Desert Forest on Hills	69	21.07	29.39
Polar Dry Forest on Plains	18,229	21.64	30.50
Cool Temperate Moist Shrubland on Mountains	2,75,865	22.13	37.88
Subtropical Desert Shrubland on Mountains	20,822	22.38	32.66
Cool Temperate Moist Sparsely or Non-vegetated on Mountains	1,39,267	25.79	38.85
Subtropical Desert Shrubland on Tablelands	462	28.17	44.38
Polar Moist Snow and Ice on Mountains	2,98,440	33.44	42.67
Boreal Moist Snow and Ice on Mountains	32,729	36.21	39.67
Cool Temperate Moist Snow and Ice on Plains	195	41.28	41.57
Cool Temperate Moist Snow and Ice on Tablelands	306	51.36	56.59
Boreal Moist Snow and Ice on Plains	540	52.79	52.98
Cool Temperate Moist Snow and Ice on Mountains	10,711	54.78	60.09
Boreal Moist Snow and Ice on Hills	175	61.17	61.17
Cool Temperate Moist Snow and Ice on Hills	1314	71.3	77.49

both defined and mapped as a combined biotic/abiotic complex where the biota are represented by matrix-forming vegetation assemblages and the abiotic environment is described in terms of climate and physiography.

The sequential development of the ecosystems through a climate→landform→vegetation progression follows the ecological importance of these features in the structural determination of ecosystem type. The climate and landform establish the primary and secondary controls on the regional distribution of vegetation (Bailey, 2009; Sayre et al., 2014). The observed patterns of vegetation distributions therefore reflect a biotic response to the physical environmental potential established by the climate regime and terrain characteristics.

**Table 5**

The amount of conversion of the World Ecosystems grouped by their vegetation/land cover attribute. The original distribution of the forestlands, shrublands, grasslands, bare areas, and snow and ice was calculated as the sum of their current distribution plus the area of those classes that have been converted into croplands and settlements. Potential natural vegetation data were used to allocate cropland and settlement classes into the vegetation classes.

Vegetation/Land Cover	Current (Actual) Area (km <sup>2</sup> )	Converted (Potential) Area (km <sup>2</sup> )	Conversion (%)
Forestlands	43,774,999	15,012,029	25.5
Shrublands	16,329,179	2,020,400	11.0
Grasslands	12,675,276	8,917,519	41.3
Sparsely or Non-vegetated	29,672,029	583,162	1.9
Snow and Ice	2,284,798	104	0.005

**Table 6**

Representation of the 1225 realm-segregated World Ecosystems in protected areas for each biogeographic realm (excluding Antarctica). Representation levels include unrepresented (0%), under-represented (1%–8.5%), moderately represented (8.5%–17%), and well represented (>17%). Representation results are presented for both the less inclusive (IUCN I-IV protected areas only) and the more inclusive (all protected areas) approaches.

Biogeographic Realm	Number of Ecosystems in Realm	Number of Ecosystems With No (0%) Representation		Number of Ecosystems With >0% and ≤8.5% Representation		Number of Ecosystems With >8.5% and ≤17% Representation		Number of Ecosystems With > 17% Representation	
		IUCN I-IV	All Protected Areas	IUCN I-IV	All Protected Areas	IUCN I-IV	All Protected Areas	IUCN I-IV	All Protected Areas
Nearctic	219	33	9	112	69	27	50	47	91
Neotropic	226	38	17	150	89	18	45	20	75
Palaearctic	264	64	42	167	75	28	72	5	75
Afrotropic	163	14	3	87	42	25	36	37	82
Indomalayan	131	29	23	44	34	33	26	25	48
Australasia	138	10	7	71	37	30	22	27	72
Oceania	84	61	22	7	19	6	12	10	31

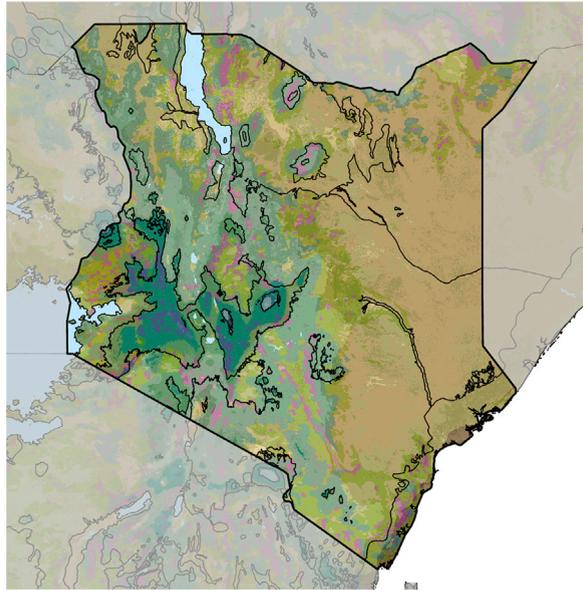
#### 4.2. World Ecosystems and World Wildlife Fund Ecoregions

The World Ecosystems are a delineation of the set of unique physical environments to which biota, and vegetation in particular, respond and distribute. The World Ecosystems are not delineated based on species distributions, community assemblages, or other biogeographic criteria, and in this way differ considerably from WWF ecoregions. WWF ecoregions are “relatively large units of land containing a distinct assemblage of natural communities and species” (Olson et al., 2001). The 867 terrestrial WWF ecoregions (Olson et al., 2001), now revised to 846 terrestrial ecoregions (Dinerstein et al., 2017), partition the planet into a set of large ecologically meaningful regions, but do not provide additional spatially explicit, occurrence-level information on ecosystems contained within ecoregions.

There are notable differences between the World Ecosystems data and the WWF ecoregions data. One difference pertains to the derivation of the units. The ecoregions are expert-derived over a multi-year, broadly consultative process, and their uptake, use, and longstanding popularity are a testament to the strength of the expert approach that was used. In contrast, the World Ecosystems are data-derived and result from reproducible combinations of standardized spatial data layers.

Another difference pertains to the scale (granularity) of the units. Whereas ecoregions are relatively coarse, macroscale entities, the World Ecosystems are a relatively high spatial resolution (250 m) characterization of all land on earth, and as such they represent on-the-ground occurrences of globally distinct biophysical and biogeographic settings. Ecoregions are large areas which have been delineated using biogeographic criteria, but which provide no information on what actually exists on the ground at any particular location. There is considerable local and regional environmental heterogeneity within ecoregions. For example, Fig. 9 shows both the WWF ecoregions and the World Ecosystems of Kenya. For Kenya, there are 13 ecoregions that fall completely or partially within the country, and there are 98 World Ecosystems in the country. This graphic shows that the ecoregions are not at all homogenous in terms of internal variation in ecosystem composition, and rather that a number of different ecosystems are found in each individual ecoregion. This consistent finer scale mapping offers much better opportunities for the prioritization of fine-scale action.

Another fundamental difference between the use of ecoregions and World Ecosystems in global conservation priority setting pertains to the nature of the units themselves. Ecoregions are understood to be derived from a consideration of the species, communities, and ecosystems that they contain. On the other hand, the World Ecosystems derive from an identification of biophysically distinct areas. The physical environmental potential in these areas largely determine what biota will be found there, and so conserving abiotically distinct areas and their associated vegetation assemblages is a common approach to conserving biodiversity. This thinking is embodied in what has come to be called the Conserving Nature's Stage (CNS) approach, (Beier et al., 2015), which advocates the use of physical environmental variables such as climate diversity and geodiversity (landform, soil types, etc.) in biodiversity conservation approaches.



**Fig. 9.** The WWF ecoregions (13, delineated by black lines) and the classes of World Ecosystems (98, represented as different colors) of Kenya. Each ecoregion contains a variety of ecosystems.

#### 4.3. Progress towards Aichi Target 11 – is the ecosystem protection glass half empty or half full?

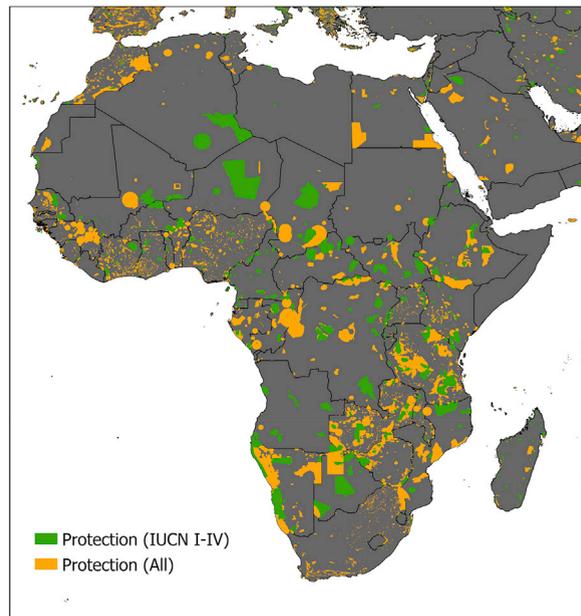
The true conservation status of World Ecosystems in protected areas is a function of management effectiveness, but standardized, globally comprehensive data on management effectiveness do not exist, and IUCN management category is used as a proxy. Despite this caveat, our analysis paints two contrasting pictures with respect to conservation of global ecosystems. When using only the subset of all protected areas which are assumed to offer more effective biodiversity protection measures, half of the planet's terrestrial ecosystems are less than 5% protected, far from the 17% Aichi target. The less inclusive gap analysis results demonstrate that the majority of global terrestrial ecosystems are significantly under-represented in the global protected areas network based on the Aichi Target 17% protection goal (<https://www.cbd.int/sp/targets/>). This general lack of representation of ecosystems in protected areas is a concern, and adds to the increasing body of evidence (IPBES, 2019) that global biodiversity at ecosystems and species levels is insufficiently conserved (Butchart et al., 2015; Kuempel et al., 2016; Venter et al., 2018; Goettsch et al., 2019). We acknowledge that protected areas are established for a variety of reasons, but they generally fall short of protecting representative ecosystems at both the global and biogeographic realms levels. It is also important to note that the eight most protected ecosystems are all snow and ice classes. This result is consistent with the finding of Aycrigg et al. (2013) that protected areas in the United States show a skewed distribution towards high elevation and low productivity soils, underscoring an increasing criticism that protected areas are differentially protecting 'rocks and ice'. The 19 ecosystems that exceed the 17% Aichi target are almost all found in inhospitable environments with polar temperatures or desertic moisture levels.

On the other hand, ecosystem protection increases considerably when using all protected areas in the global gap analysis. If all protected areas are effectively conserving global ecosystems, then a third of the ecosystems have exceeded the Aichi 17% target, and another third are not far behind with a >8.5% representation. Only five of the planet's ecosystems are entirely unrepresented in global protected areas by this approach.

The choice of protected areas to include in the assessment of progress towards Aichi Target 11 is therefore a very important consideration, and we encourage careful evaluation of the conservation effectiveness of protected areas when making those assessments. The magnitude of that effort is visually presented in Fig. 10, which shows the protected areas of Africa. There are two fundamental questions to consider when interpreting Fig. 10: 1) are the IUCN I-IV protected areas (depicted in green) truly conserving the ecosystems they contain, as is generally assumed?, and 2) which of the remaining protected areas (orange) are also effectively conserving ecosystems? The answer to that question would suggest the ideal set of protected areas that should be used in the representation analysis for assessing the progress of African ecosystems against the Aichi 17% target goal.

#### 4.4. Data availability

The new World Ecosystems data are available in the public domain (<https://rmgsc.cr.usgs.gov/outgoing/ecosystems/Global/>) in their full spatial resolution (250 m) and at both the globally aggregated (431 ecosystems) and realm-



**Fig. 10.** The protected areas of Africa. Green areas are IUCN management category I-IV protected areas, and orange areas represent additional protected areas that include IUCN management category V and VI, as well as other protected areas lacking an IUCN management category designation.

segregated (1779 ecosystems) levels. The full set of attributes from the input layers (World Climate Regions, World Landforms, and World Vegetation/Land Cover) are included with the World Ecosystems layers.

#### 4.5. Limitations to the approach

We have delineated terrestrial ecosystems on Earth using definitions and mapping criteria developed by the IPCC. While this fidelity to the IPCC criteria has resulted in a set of robust and authoritative units, it also precluded the use of other variables which potentially influence the distribution of biota. We used only two climatic variables, annual temperature and annual precipitation, to describe the thermotypic and ombrotypic nature of the landscape. There are many other bioclimatic variables that could have been contemplated, including those related to seasonality and climatic extremes. It was not our objective to identify the best set of abiotic variables for prediction of local vegetation assemblages, rather to identify unique combinations of climate regions, landforms, and vegetation.

We aggregated several landform classes into four simple macro-landform types (plains, hills, mountains, and tablelands) and in so doing we may have missed out on finer scale terrain differences that influence the vegetation. For example, low mountain forests would likely differ from high mountain forests, but in our classification they would not be separated. Again, however, it was not our intention to find the best set of abiotic variables in any particular place that best predicted the vegetation occurring there.

Finally, we acknowledge that there are different ways to define and map ecosystems. We have taken the structural approach, that is mapping ecosystems by mapping, and subsequently integrating, their biotic and abiotic structural elements. It may also be possible to map ecosystems by their functional properties, e.g. productivity, water and nutrient fluxes, trophic relationships, etc. An analysis of the new World Ecosystems from an ecosystem function perspective would be valuable and is encouraged along the lines of future work.

## 5. Conclusion

The new World Ecosystems resource is a high resolution (250 m) spatially explicit delineation of the set of unique combinations of climate and terrain which establish the physical potential of the environment, and the associated vegetation that occurs in those areas in response to the environmental gradients. Of the 431 global ecosystems that were identified and mapped based on abiotic and biotic factors, 278 were natural or semi-natural ecosystems. Of these 278 ecosystems, 259 (93%) were less than 17% represented in strictly conserved protected areas, and as such the Aichi target of 17% protection is unmet across almost all global terrestrial ecosystems. On the other hand, when considering all protected areas, 91 ecosystems (33%) exceed the 17% target and an additional 105 (38%) are more than half way (>8.5% protection) towards the Aichi goal.

We believe that the new World Ecosystems data are appropriate for geographic conservation priority setting, and The Nature Conservancy is incorporating the data into their global planning efforts. Whether the planning scale is global, by

biogeographic realm, or by nation, the unrepresented and under-represented ecosystems at the Aichi Target 17% protection level could be considered as strong candidates for future conservation investment.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgments

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The authors are grateful for the journal-provided reviews and for helpful comments from Terry Sohl and Robin White of the U.S. Geological Survey.

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